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DEXTERITY ANALYSIS AND ROBOT HAND DESIGN

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ABSTRACT

Understanding about a dexterous robot hand's motion ranges is important to the precision grasping and precision manipulation [4]. This paper presents an object oriented study for a planar robot hand on the ranges, measured with respect to the palm, of position reaching of a point in the grasped object, and of rotation of the object about the reference point. In this paper we introduced the rotational dexterity index and dexterity chart. We developed an analysis procedure for calculating these quantities. We also developed a design procedure for determining the hand kinematic parameters based on a desired partial or complete dexterity chart. These procedures have been tested in detail for a planar robot hand with two 2- or 3-link fingers. We have shown that the derived results are useful to performance evaluation, kinematic parameter design, and grasping motion planning for a planar robot hand.

1. Introduction

Many robot manipulation tasks require a robot hand to have dexterity in fingers' arrangement and movement. These tasks include non-grasping manipulation such as playing piano and pushing object, and grasping manipulation such as power grasping and precision grasping [1, 3, 5, 6]. In this study we are interested in the dexterity for precision grasping. The precision grasping logically implies that the grasped object can move delicately with respect to the palm. Disregarding the grasping capability, grasping stability, optimal grasping configuration, etc., for which there exist many studies in literature, we further limit ourself to the study of the motion range of the grasped object.

Compared with the robot arm motion, the object's motion relative to hand is usually small. However, for such relative motion the range of position reaching of a point on the object and the range of rotation of the object about the point at a given position is still a basic and important problem. While there are many studies on the robot arm's primary and secondary workspace (see the definition by B. Roth [8] and K.C. Gupta and B. Roth [2]), there are relatively few studies on hand motion range reported in the literature, among which the work by J. Kerr and B. Roth [4] provides us a starting point.

Unlike a robot arm, in conducting motion range for a robot hand, the shape and size of grasped object must be taken into account, since the hand and the grasped object constitute one motion system. [4] has studied the position reaching of a hand with two and three fingers. They assumed a line or a triangle with vertices corresponding to the two or three grasping points. This gives a relatively simple model, however, the influence from the interference between the fingers and the grasped object is neglected to a large extent.

Besides the range of position reaching of a point in the object, the range of rotation of the object about the reference point at each position should also be determined. Since the grasped object usually has very limited range of rotation, it is not appropriated for one to seek a counterpart in precision grasping for primary workspace which exists for a robot arm. Instead, one need to find the distribution of different rotation ranges in the positionally reachable space.

This paper presents our study guided by above thoughts for a planar robot hand. The paper is divided into two parts: dexterity analysis and design application. In the analysis part, we have selected a circle of suitable size as a testing object, defined a rotational dexterity index for the grasped object at a given position, represented the spatial distribution of rotational dexterity over the workspace by a dexterity chart. Detailed analyses are conducted for a planar hand with two 2- or 3-link fingers. In the design application part, we presented a methodology for designing the kinematic parameters of a planar hand from a desired partial or complete dexterity chart. Depending on the number of controlling points in the dexterity chart, we have shown that the optimal approximate solution in the sense of least square errors can be obtained. The technique of selecting initial value and final solution modification have also been discussed.

2. Dexterity Analysis

We assume in this analysis that the contacts always occur at the finger tips and there is no slipping at the finger tips during motion. For the most part, we also neglect the size of the finger tip. Its influence will be discussed near the end of this section.

In addition to these assumptions, depending on tasks there are various objects with different geometric shapes and sizes. For a particular application, it is appropriate to test directly on the grasped object. In this paper we select a circle as a testing object based on three reasons: (1) without a particular task in mind, a circle is always one of the most simple and common planar objects (or component objects); (2) the simplicity in analysis due to using a circle does not prevent the developed methodology to be extended to other testing objects; (3) the motion range analysis for a circle always provides the lower bound of the motion ranges for any inscribed objects, though this is under the assumption that their contacts are positioned coincident with the circle.

The size of a manipulated object will affect the dexterity measure. The dexterity of a hand decreases as the size of the object increases. In order to study the influence on dexterity due to hand configuration instead of hand dimension, we let the diameter of the testing circle to be proportional to the average length of the fingers, while the proportional coefficient is chosen heuristically as 0.5. From calculation for many cases in which the hands have two homogeneous 2-link fingers, we noticed that when the proportional coefficient varies around 0.5, a scalar dexterity measure changes linearly.

2.1 Dexterity Analysis of A Planar Hand With Two 2-Link Fingers

When the dimension of the finger tip is not negligible, a planar hand with two 2-link fingers can not turn an object without slipping, since the finger's position and orientation can not be controlled at the same time. To turn an object by pure rolling between the fingers and the object, the minimum number of joints required is two for one finger and three for the other. However, to illustrate our analysis procedure a hand having two homogeneous 2-link fingers with pointed tips is sufficient.

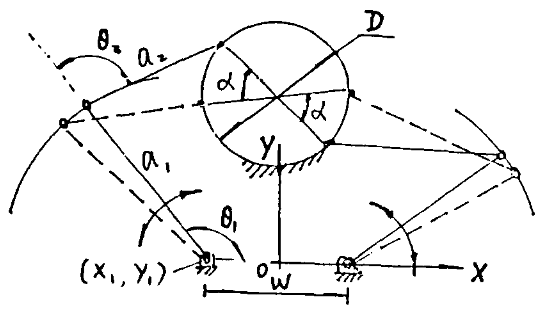

Figure 1

A kinematic model of a hand with two 2-link fingers grasping a ball is shown in figure 1. Since those two fingers are symmetrical, we need to only look at one finger. Let us define, for finger 1, θ_i to be the rotation angle for joint i; a_i the length of link i; (X_1, Y_1) the coordinates of finger base; and (X_b, Y_b) the coordinates for finger tip with respect to palm coordinates. These variable and parameter symbols are consistent throughout this paper.

The transformation matrix from the finger tip coordinates to the palm coordinates, takes a form [7]

$$\begin{bmatrix} M_x & N_x & X_b \\ M_y & N_y & Y_b \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & X_1 \\ \sin\theta_1 & \cos\theta_1 & Y_1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & a_1 \\ \sin\theta_2 & \cos\theta_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & a_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \ldots\ldots (1)$$

We have two equations from (1)

$$(X_b-X_1)\cos\theta_1+(Y_b-Y_1)\sin\theta_1 = a_2\cos\theta_2+a_1 \quad \ldots\ldots (2)$$

$$(Y_b-Y_1)\cos\theta_1-(X_b-X_1)\sin\theta_1 = a_2\sin\theta_2 \quad \ldots\ldots (3)$$

The solution of θ_1 and θ_2 should however be checked against any interference between the object and the fingers. If two very near points on the circle can be reached by one finger, their circle-center symmetrical points can be reached by the other finger, and there is no interference between the ball and fingers, we can assume that a corresponding small arc length on the circle is reachable by fingers. Moving the finger around the circle and summing up all reachable small segments, the total reachable arc length can be obtained, which is directly proportional to the range of the rotation angle of the object, since the contact points are fixed between the fingers and the circle. For a planar precision grasping, we define the Rotational Dexterity Index at a position as

$$RDI = (\text{Sum of reachable Arc Length}) / (2R\pi) \quad \ldots\ldots (4)$$

The workspace of the hand is defined as the motion range which the reference point of the testing object (a center point of the circle) can reach. Many nodes can be created by dividing the workspace into a collection of small areas. For each node the rotational dexterity index can be calculated. Then, a set of loci of the nodes having equal vales of rotational dexterity index can be obtained. Within the range of the workspace, these curves represent the spatial distribution of different degrees of rotational dexterity. We name the ares within one curve of rotational dexterity index p as Workspace of Rotational Dexterity Index ($WRDI_{RDI=p}$).

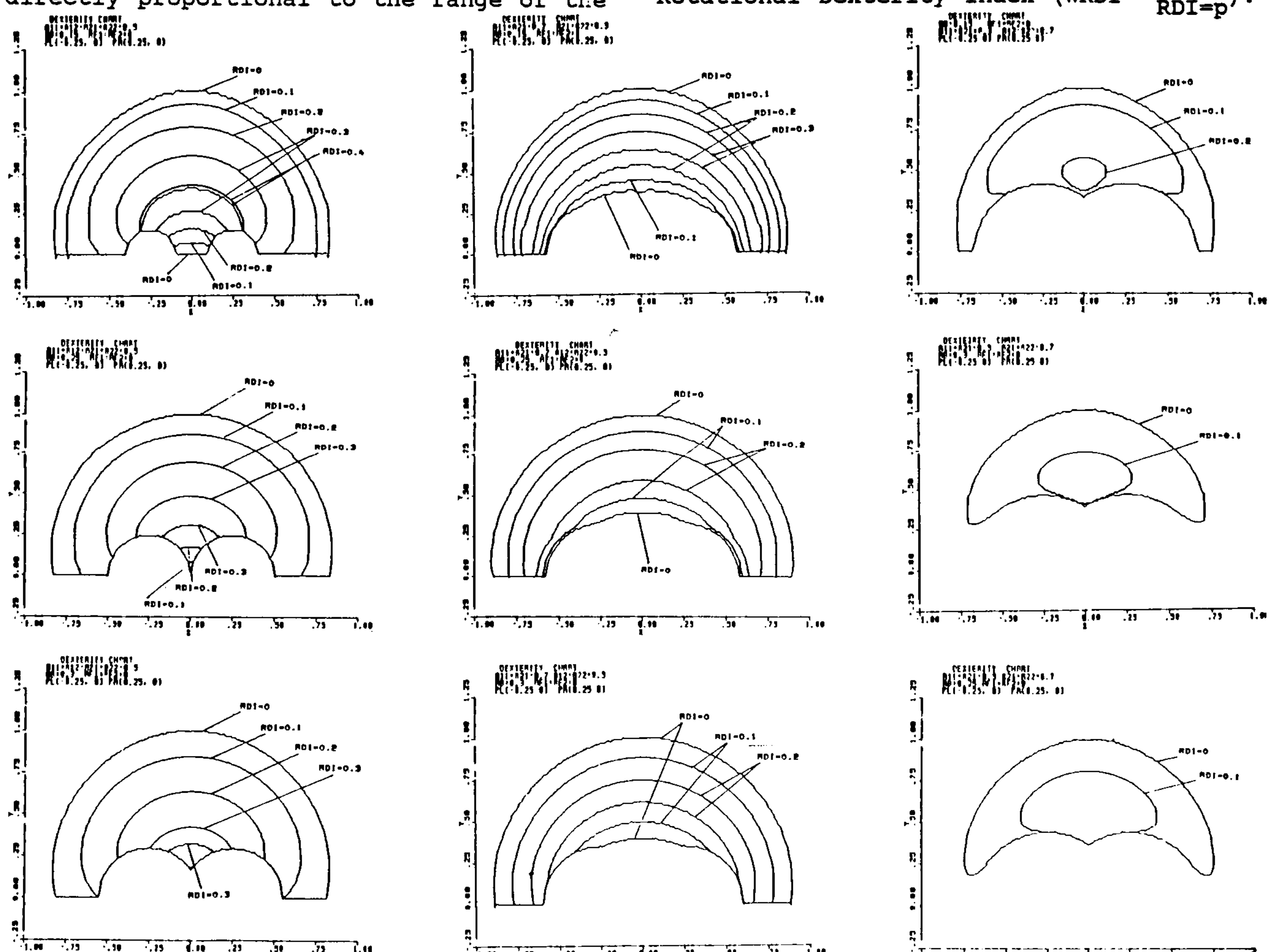

Figure 2

The WRDI distribution can be very effectively expressed through a chart, we call it the dexterity chart.

Figure 2 shows some dexterity charts that present the dexterity of some hands with two homogeneous two-link fingers. In the figures we choose the increase step for RDI as 0.1. From the comparison of the charts we can see clearly that the link parameters have big influence over the manipulating capability of a hand. For a planar hand with two non-homogeneous fingers, a non-symmetrical dexterity chart can be obtained, such as in the figure 3. These dexterity charts are very useful in comparing dexterity of two hands, in programing the motion of a manipulated object, and in designing a hand.

The dexterity of a hand may be expressed by a scalar. We define one scalar as the summing up all the areas in different WRDI. That is,

$$DEX = \Sigma\ (i+1)\ AREA_{RDI=i*step} \qquad \cdots\cdots(5)$$

Where the step can be 0.1 or other value we prefer. The another obvious choice is that define DEX as the average rotational dexterity index.

2.2. Dexterity Analysis of A Planar Hand With Two 3-Link Fingers

The analysis procedure used for the planar hand with two 2-link fingers can be easily extended to a planar hand with two 3-link fingers.

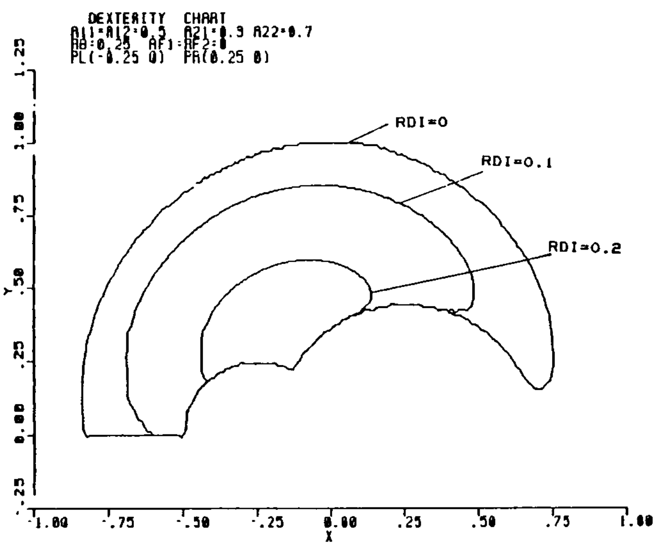

Figure 3

The kinematic model of a two 3-link finger hand is shown in Figure 4. The transformation matrix from finger tip coordinate system to palm coordinate system can be expressed as

$$\begin{bmatrix} M_x & N_x & X_b \\ M_y & N_y & Y_b \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & X_1 \\ \sin\theta_1 & \cos\theta_1 & Y_1 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & a_1 \\ \sin\theta_2 & \cos\theta_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & a_2 \\ \sin\theta_3 & \cos\theta_3 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & a_3 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \cdots\cdots(6)$$

From (6) we obtain three independent equations

$$-M_x a_2\cos\theta_3 + N_x a_2\sin\theta_3 + (X_b - M_x a_3 - X_1) = a_1\cos\theta_1$$
$$-M_y a_2\cos\theta_3 + N_y a_2\sin\theta_3 + (Y_b - M_y a_3 - Y_1) = a_1\sin\theta_1$$
$$\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2 = M_x\cos\theta_3 - M_y\sin\theta_3 \qquad \cdots\cdots(7)$$

Because the left side of equation (6) consists of known parameters, the variable θ_1, θ_2 and θ_3 are solvable.

The procedure used for dexterity analysis of a hand with two 2-link fingers can be used now for the analysis of the hand with two 3-link fingers. We need only to follow each steps presented in the previous section.

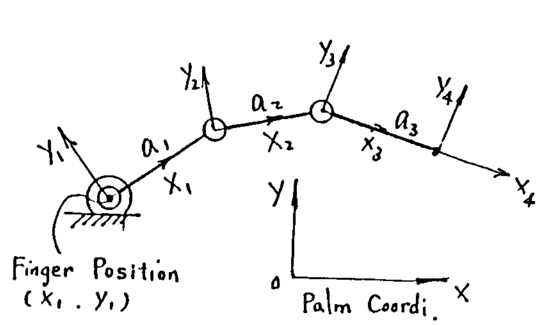

Figure 4

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2.3 The Effect of Finger Tip Dimension on Dexterity

The method can be extended to take into account the dimension of finger tips. Figure 5 shows that when the finger tip is of circular type, we can choose the equivalent radius of the manipulated circle as $R^*=R+r$, then above procedure for dexterity analysis can still be used. An additional value δRDI should be added to RDI, $\delta RDI=\delta\phi\ r/R$, where $\delta\phi=\phi_1-\phi_2$ is due to pure rolling between the finger and the circle.

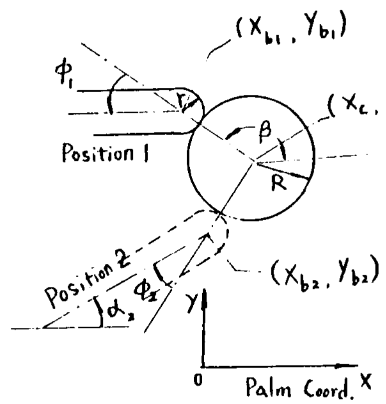


Figure 5

2.4. Dexterity Analysis of A Planar Multifinger Hand

A multifinger hand can reposition some of its finger contacts with respect to the grasped object, so it may have much large WRDI of RDI=1.0.

If we assume all fingers keep contacting while turning a circle, the previous methodology can be applied directly.

3. Application for Kinematic Parameters Design of Planar Robot Hands

Given the number of fingers, numbers of links for each finger, and finger tip positions, there are still the kinematic parameters of a planar hand need to be determined. These parameters include palm size (or locations of finger bases), the length of each finger link, and the diameters of the sphere (semisphere) attached on finger tips.

We present here a design methodology which is based on a partial or complete desired dexterity chart. Such partial dexterity chart can be obtained by selecting several positions on the boundaries of different WRDI. For an arbitrarily given object and a dexterity chart, while we can design a hand to follow accurately few controlling points in a dexterity chart, it is not feasible to have a hand whose dexterity chart matches exactly an arbitrarily given one. We develop an approximate design method which results in a hand with the dexterity chart that has minimum deviation from a given one.

3.1 Design of A Planar Hand with Two 2-Link Fingers

The configuration of a planar two-link finger is the same as shown in figure 1. As we illustrated in figure 1 and figure 5, let (X_1, Y_1) be the coordinates for the base of finger 1 in the palm coordinate; (X_c, Y_c) be the coordinates for the center point of the circle; β be the angle between the X axis of the palm frame and the line through the circle center and contact point of finger1; and r be the radius of the sphere attached on the tip of finger 1. The transformation matrix from finger tip coordinate system to the palm coordinate system takes the same expression as in (1). Except that $X_b=X_c+(R+r)\cos\beta$ and $Y_b=Y_c+(R+r)\sin\beta$. Premultiply both sidesof the equation by the inverse matrix associated with θ_1. Three independent equations are obtained.

$$a_2\cos\theta_2+a_1 = \cos\theta_1[X_c+(R+r)\cos\beta-X_1]+ +\sin\theta_1[Y_c+(R+r)\sin\beta-Y_1] \quad ......(8)$$

$$a_2\sin\theta_2 = -\sin\theta_1[X_c+(R+r)\cos\beta-X_1]+ +\cos\theta_1[Y_c+(R+r)\sin\beta-Y_1] \quad ......(9)$$

$$\cos\theta_2 = M_x\cos\theta_1+M_y\sin\theta_1 \quad ......(10)$$

Because $M_x=\cos\alpha$ and $M_y=\sin\alpha$,where α is the angle between last link of the designed finger and the X axis of the palm frame, the equation (10) can be rewritten as

$$\alpha = \theta_1 + \theta_2 \quad ...... (11)$$

Given one position in a dexterity chart, there are three equations and six unknowns (X_1, Y_1, a_1, a_2, θ_1 and θ_2).For n positions in the dexterity chart, there are 3n equations and 4+2n unknowns. Therefore, for 4 given positions in a dexterity chart there exists an exact solution for finger parameters.

When the number of given positions are over 4, the above equations are overconstrained. we can obtain approximate solutions by using regression methods, in which one of the simplest is least square method. Our objective is to seek suitable a_1, a_2, X_1, Y_1, θ_1, and θ_2, to minimize the error for equations (8), (9) and (11).

$$\min \ \Sigma \{ \cos\theta_{1i}[X_{ci}+(R+r)\cos\beta_i-X_1]+ +\sin\theta_{1i}[Y_{ci}+(R+r)\sin\beta_i-Y_1]-a_2\cos\theta_{2i}- -a_1 \}^2+\{ -\sin\theta_{1i}[X_{ci}+(R+r)\cos\beta_i-X_1]+ +\cos\theta_{1i}[Y_{ci}+(R+r)\sin\beta_i-Y_1]-a_2\sin\theta_{2i} \}^2$$

$$\text{S.T.} \quad \theta_{1i} + \theta_{2i} - \alpha_i = 0$$

$$\text{where } i = 1,2,3....n \qquad ...... (12)$$

In using least square method, we tentatively guess θ_{2i} for each position, and solve θ_{1i} from equation (11). For n positions the 2n equations from (8) and (9) can be written as in matrix form

$$\begin{bmatrix} 1 & K_{12} & K_{13} & K_{14} \\ 0 & K_{22} & K_{23} & K_{24} \\ 1 & K_{32} & K_{33} & K_{34} \\ 0 & K_{42} & K_{43} & K_{44} \\ ... & & & \\ 1 & K_{(2n-1)2} & ... & K_{(2n-1)4} \\ 0 & K_{(2n)2} & ... & K_{(2n)4} \end{bmatrix} \begin{bmatrix} G_1 \\ G_2 \\ G_3 \\ G_4 \end{bmatrix} = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ ... \\ P_{2n-1} \\ P_{2n} \end{bmatrix} \qquad ...... (13)$$

where $G_1=a_1$, $G_2=a_2$, $G_3=X_1$, $G_4=Y_1$

$$P_{2i-1}= \cos\theta_{1i}[X_{ci}+(R+r)\cos\beta_i]+ +\sin\theta_{1i}[Y_{ci}+(R+r)\sin\beta_i]$$

$$P_{(2i)}= -\sin\theta_{1i}[X_{ci}+(R+r)\cos\beta_i]+ +\cos\theta_{1i}[Y_{ci}+(R+r)\sin\beta_i]$$

$$K_{(2i-1)2} = \cos\theta_{2i}$$

$$K_{(2i)2} = \sin\theta_{2i}$$

$$K_{(2i-1)3} = K_{(2i)4} = \cos(\alpha_i-\theta_{2i})$$

$$K_{(2i-1)4} = -K_{(2i)3} = \sin(\alpha_i-\theta_{2i})$$

$$i = 1,\ 2,\ 3...n.$$

Rewriting equation (13) in brief form

$$[\ K\ ]_{(2nx4)}\ [\ G\ ]_{(4x1)} = [\ P\ ]_{(2nx1)} \qquad ...... (14)$$

Premultiplying both sides of equation (14) by matrix $[\ K\ ]^T_{(4x2n)}$,

$$[\ G\ ] = (\ [\ K\ ]^T\ [\ K\ ]\ )^{-1}\ [\ K\ ]^T\ [\ P\ ] \qquad .... (15)$$

The matrix $[\ K\ ]^T\ [\ K\ ]$ is positive definite and symmetrical. Except for singular cases it has inverse matrix.

3.2 Initial Values of Iteration

From kinematic parameters obtained by (15), actual θ_{1i} and θ_{2i} can be calculated. By iterative computation the solution will be refined each time.

The initial values of θ_{2i}'s will affect the convergence speed. In the design of a two 2-link finger, by our sign convertion, negative initial values are suggested for a left finger, and positive initial values are suggested for a right finger.

Looking at the matrix expression

$$[\ K\ ]^T\ [\ K\ ]=$$

$$\begin{bmatrix} n & \Sigma\cos\theta_{2i} & \Sigma\cos(\alpha_i-\theta_{2i}) & \Sigma\sin(\alpha_i-\theta_{2i}) \\ \Sigma\cos\theta_{2i} & n & \Sigma\cos\alpha_i & \Sigma\sin\alpha_i \\ \Sigma\cos(\alpha_i-\theta_{2i}) & \Sigma\cos\alpha_i & n & 0 \\ \Sigma\sin(\alpha_i-\theta_{2i}) & \Sigma\sin\alpha_i & 0 & n \end{bmatrix}$$

we notice that to avoid singularity we can not have all initial values of θ_{2i}'s to be zero, or to satisfy the constraints $\alpha-\theta_2=0$ or $\alpha-\theta_2=\pi/2$ for all positions.

3.3 Approaching Final Solution

The solution from the iterative method means that the finger tip can be as close as possible to the required positions for given α_i's. It is not surprise that some part of thedexterity chart will be satisfactory and some part will be not. Following three techniques can help us to improve the final solution, while using the same number of links for each finger and same number of finger for each hand.

(1) Improve α's

From (13) we know that we can not assign all α_i equal0 or $\pi/2$, otherwise the matrix $[\ K\ ]^T[\ K\ ]$ will be singular. Checking the result of computation, we can find which α is selected unappropriatelly and to which direction it needs to be modified.

(2) Repeat The Equations for Few Positions In (13)

Repeating the equations for few positions in (13) would drive the corresponding parts of the dexterity chart approach more closely to desired one, though the other parts will deviate correspondingly. This is useful for the case where some points are relatively more important.

(3) Shift The Given Positions of The Finger Tip

The resulted dexterity chart may also provide us some clues as to shift some contact positions of the finger tip, since either their requirement can not be met, or they have big negative influence over whole chart.

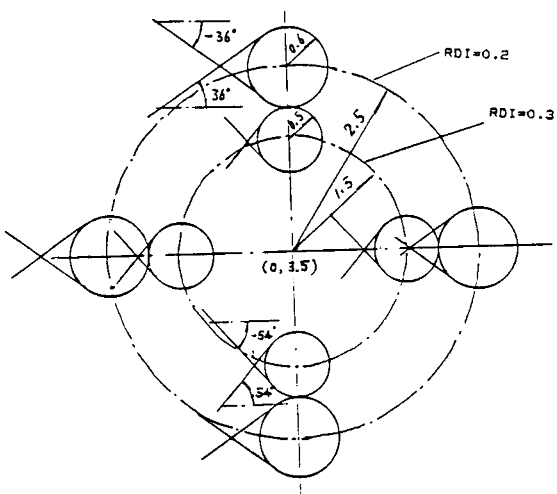
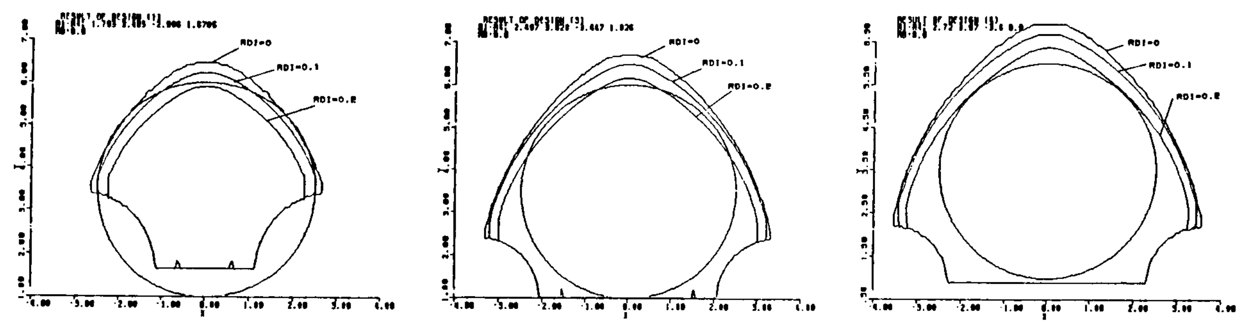


Figure 6

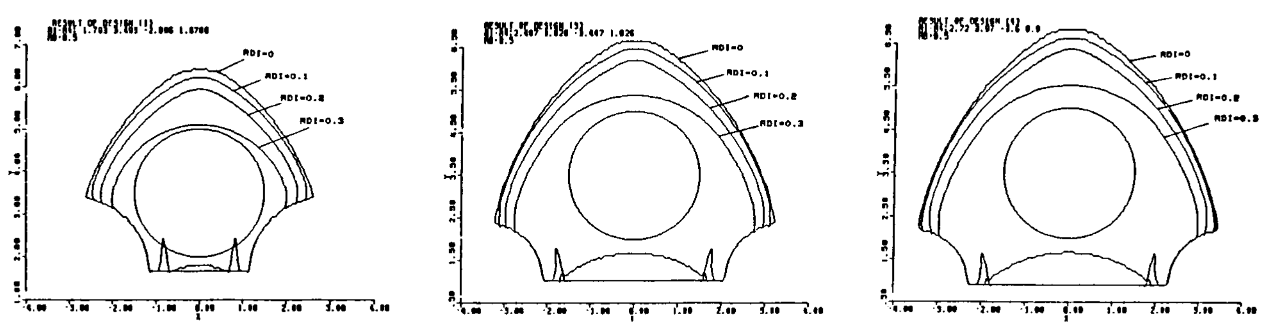
3.4 An Design Example

A hand with two 2-link fingers is designed to test our design methodology. The hand is expected to (1) have a WRDI (RDI=0.2) in a circle with radius R=2.5, for a manipulated ball with radius R=0.6; and at the same time (2) have a WRDI (RDI=0.3) in a circle with radius R=1.5, for a manipulated ball with radius R=0.5. Both of the circle centers are at the point (0, 3.5). Totally 16 positions in the dexterity chart are selected to design the hand. Because the desired dexterity chart and fingers' configuration is symmetric, only one finger need to be designed. The selection of initial positions and orientations of the last links is shown in figure 6. The process of approaching the final solution is shown in figure 7. To improve the legibility, RDI curves with larger values are not shown in the charts. Figure 7 (b) shows that the condition (2) is always satisfied, and figure 7 (a) shows how the condition (1) is approached.

Although, in the example, two manipulated objects are circles, the



(a)



(b)

Figure 7

method can be used to design a hand for manipulating several different objects with several different levels of dexterity. That is very useful for the designing of industrial robot hands.

3.5 Design of a Three Link Finger

The design method can be extended to design a three link finger.

The configuration of a planar three link finger is figure 4. The transformation matrix from finger tip coordinate system to the palm coordinate system is expressed in (6).

Considering $M_x=N_y=\cos\alpha, M_y=-N_x=\sin\alpha$,

rewrite equation (7), we have

$$\alpha = \theta_1+\theta_2+\theta_3 \quad \ldots\ldots(16)$$

$$a_1\cos\theta_1+a_2\cos(\alpha-\theta_3)+a_3\cos\alpha+X_1 = X_b \quad \ldots(17)$$

$$a_1\sin\theta_1+a_2\sin(\alpha-\theta_3)+a_3\sin\alpha+Y_1 = Y_b \quad \ldots(18)$$

When the dimension of the finger tip is considered, $X_b=X_c+(R+r)\cos\beta$ and $Y_b=Y_c+(R+r)\sin\beta$ are to be substituted into (17) and (18).

For one point on a dexterity chart there are 3 equations and 8 unknowns (X_1, Y_1, a_1, a_2, a_3, θ_1, θ_2 and θ_3). For n points there are 3n equations and 5+3n unknowns. After we assign values to 5 unknowns, we can have 3n equations with 3n remain unknowns. It is very difficult or impossible to have analytic solution, so we resort to using numerical method.

In using the least square method we have to assign two θ's for each position, and the third θ can be solved from equation (16). Equations (17) and (18) can be used to construct a matrix equation

$$[\ K\ ]_{(mx5)}[\ G\ ]_{(5x1)} = [\ P\ ]_{(mx1)} \quad \ldots(19)$$

where m=2n

$$G_1=a_1,\ G_2=a_2,\ G_3=a_3,\ G_4=X_1,\ G_5=Y_1$$

$$K_{(2i-1)1} = c\theta_{1i}$$

$$K_{(2i-1)2} = \cos(\alpha_i-\theta_{3i})$$

$$K_{(2i-1)3} = \cos\alpha_i$$

$$K_{(2i)1} = s\theta_{1i}$$

$$K_{(2i)2} = \sin(\alpha_i-\theta_{3i})$$

$$K_{(2i)3} = \sin\alpha_i$$

$$K_{(2i-1)4} = K_{(2i)5} = 1$$

$$K_{(2i-1)5} = K_{(2i)4} = 0$$

The matrix [G] can be expressed as

$$[\ G\ ] = (\ [\ K\ ]^T\ [\ K\ ]\ )^{-1}\ [\ K\ ]^T\ [\ P\ ] \quad \ldots\ldots(20)$$

The rest of the steps are similar as presented for designing a 2-link finger.

3.6 Other Issues On Design

1. Design of Multifinger Hands

In the above procedure a hand is designed with one finger at a time, so there is no difference between designing a mlutifinger hand and designing a two finger hand. However, the chance of interference will increase as the finger number increase.

2. Selection of The Size of Finger Tip

Theoretically, we can design the diameter of a circular finger tip using the equation (3). However, sometime the result is not feasible. The better way is we first select the diameter of the finger tip according to the size of the manipulated object, Then check whether the result is satisfactory.

4. Conclusion

Inspired by the work on dexterous robot hand workspace [4], we proceeded an object oriented study for a planar hand on the range of position reaching of a point on the grasped object, and the range of rotation of the object about the reference point. Both ranges are measured with respect to the palm.

In this paper, for each position of the reference point, the percentage of one revolution that object can rotate about the reference point with respect to the palm is defined as rotational dexterity index for that point. The distribution of such rotational dexterity index over the whole positionally reachable space is expressed in a dexterity chart, which includes contours of different index values.

In addition to using dexterity chart for hand performance evaluation, we also presented an design procedure for determining the kinematic parameters of a planar hand with revolute joints based on a desired partial or complete dexterity chart. Least square error iterative method, its initial value selection and final solution improvement have been stressed.

The dexterity analysis and design application are presented in a case study format, in which a planar hand with two 2- or 3-link fingers have been investigated in detail.

Although the methodologies are developed for dexterity analysis and design of planar hands, they can be extended to the spatial hands for the same purpose.

The methods are useful in the analysis, design and motion planning of industrial robot hand for assembly tasks or some other tasks in which precision grasping and manipulation are needed.

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